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Direct Detection of Dark Matter: Past, Present and Future 1.

Shared with Tom Shutt

Historical perspective

- The emerging mystery of the nature of dark matter
- Emerging recognition that this is "Physics Beyond the Standard Model"

Where we are and challenges ahead:

- Four broad classes of models but no convincing hint so far
- US G2 + equivalent world wide

Where are we going?

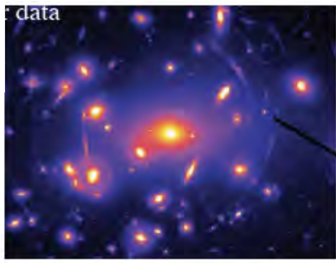
- Reaching the neutrino floor
- Other creative ideas

The Emerging Mystery of Dark Matter

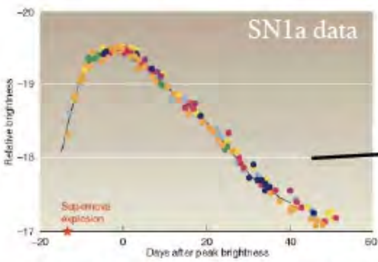
From Zwicky (1933), Vera Rubin (1970), Faber-Gallagher (1979)
=>Convincing evidence for dark matter

http://physics.ucsc.edu/~joel/Ay/214/Jan12-Primack-DM-History.pdf

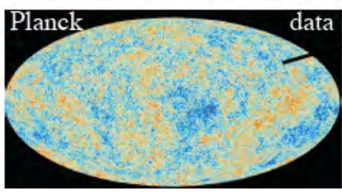
Clusters

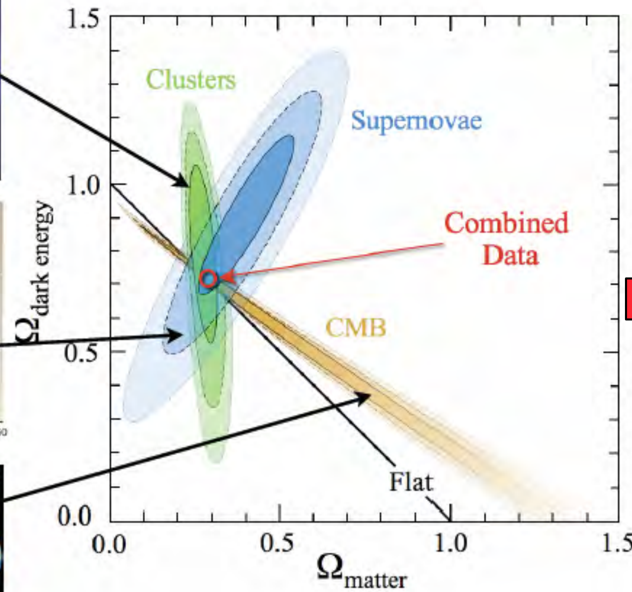


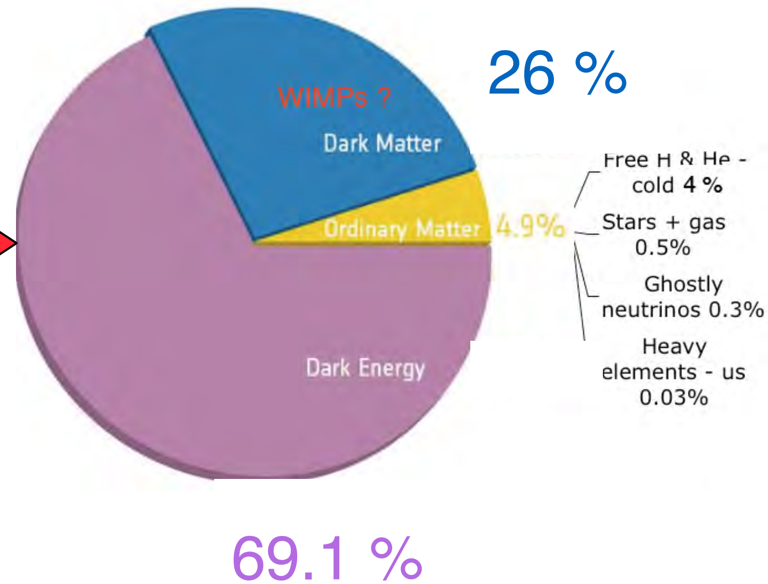
SN1a



CMB







The Ultimate Copernican Revolution

≠ Not made of ordinary matter! (Big Bang Nucleothesis, CMB)
Somewhat eclipsed by the discovery of Dark Energy 1998

Standard Cosmological model Lambda CDM!

Not light neutrinos! “Cold”=non relativistic at time of galaxy formation.
Extremely successful. No unambiguous sign of special properties
Dwarf galaxies: core, too big to fail? (Profumo)

The rise of Nuclear/ Particle Astrophysics

Emerging recognition that Dark Matter + Dark Energy requires "Physics Beyond Standard Model"

Could be problem with Gravity

- Unlikely for dark matter:
  - segregation of matter from dark matter, fluid like properties
  - failure of MOND and its relativistic generalization
- Quite likely for dark energy
  - w≈-1, cosmological constant like
  - fundamental of the energy of vacuum: a not understood effect of quantization of gravity? or energy stored in additional dimensions

Could it be particles produced in the early universe?

- Dark Matter
  - Seminal ideas from B Lee and S. Weinberg 1977, Silk and Srednicki, 1984
  - Goodman and Witten Jan 85: Direct detection is possible!
    - Proper account for coherence factors in neutrino scattering
  - Convergence with new low temperature technologies for coherent neutrino
    - Drukier and Stodolsky Dec 84
    - Cabrera, Krauss, Wilzcek, Dec 84
    - Rigberg Castle (LTD 1) March 87
  - Contrary to our naive expectation, nuclear recoils produce ionization
    - Ge: IGEX, Oroville exclude rapidly heavy Dirac and scalar neutrinos
    - Nuclear recoil discrimination (Shutt et al. 1992)
- Dark Energy from new field ???? Why w≈-1?

What kind of particle?

Particles in thermal equilibrium + decoupling when non-relativistic

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_{DM} h^2 = \frac{3 \cdot 10^{-27} cm^3/s}{\langle \sigma_A v \rangle} \qquad \Omega_{DM} \approx 25\% \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale

=> significant amount of dark matter

Weakly Interacting Massive Particles

Dark Matter could be due to TeV scale physics

A dark sector may be with dark matter—anti dark matter asymmetry

If similar to baryon anti-baryon asymmetry (Kathryn Zurek)

$$\rho_{DM} \approx 5 \times \rho_{baryon} \Rightarrow M_{DM} \approx 5 \text{ GeV/c}^2$$

Physics could be as complex as our ordinary matter sector:

if light mediator could be at small masses

Could detect these by scattering of galactic dark matter on a suitable target in laboratory

Sterile neutrino as warm Dark Matter

May not help. 3.5keV line in question (Profumo)

Athermal production: e.g., result of spontaneous symmetry breaking

Main example Peccei Quinn axions to dynamically restore CP in QCD

But broader class "axion like" particles (subeV Dark Matter Workshop)

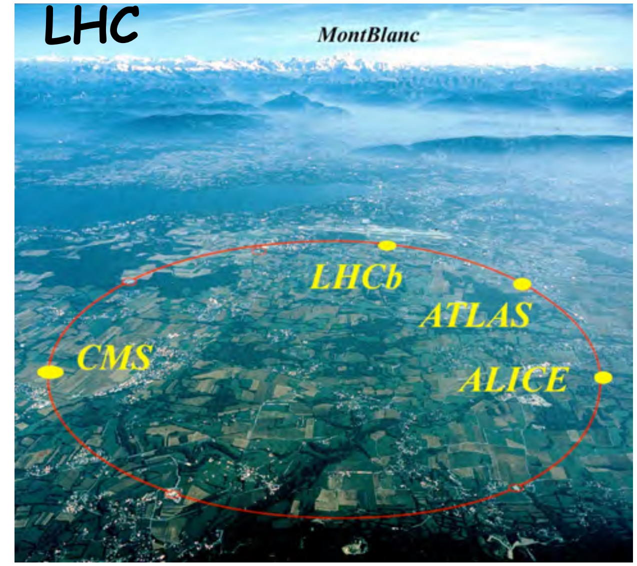
4 Complementary Approaches

Cosmological Observations

Planck

Keck telescopes

Dark Matter
Galactic Halo (simulation)



WIMP production on Earth

VERITAS, also HESS, Magic + IceCube (ν)

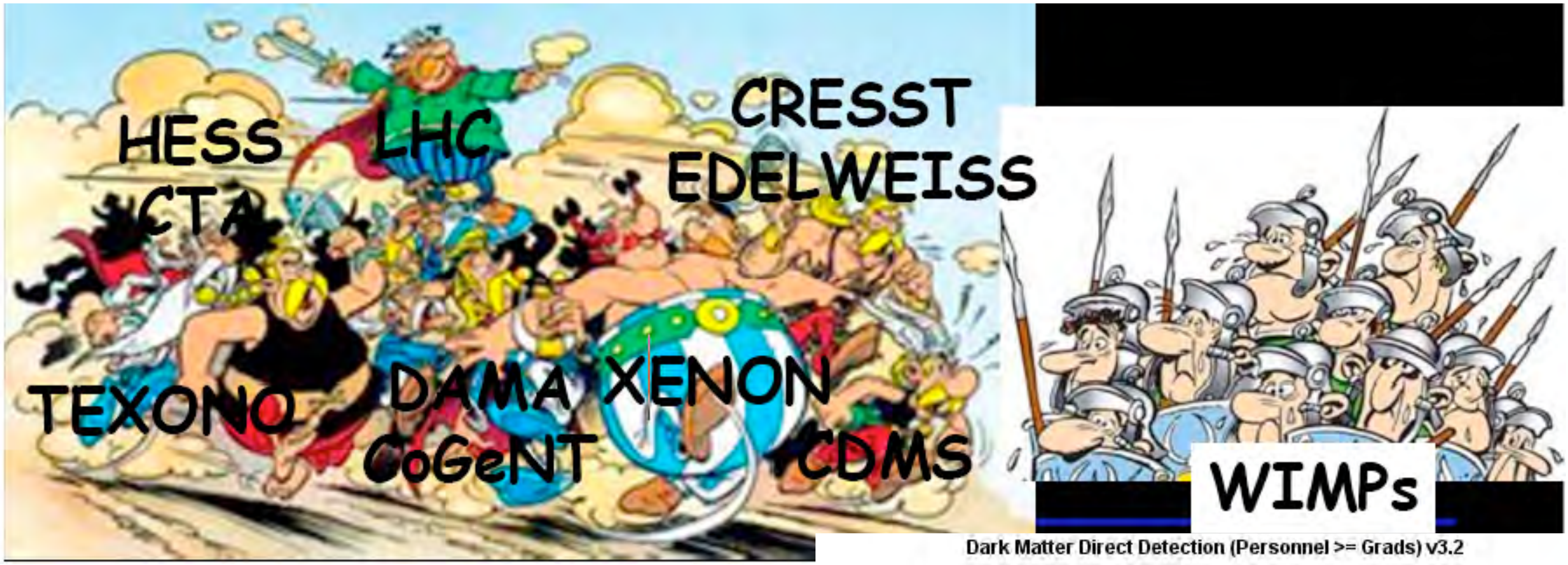
WIMP annihilation in the cosmos

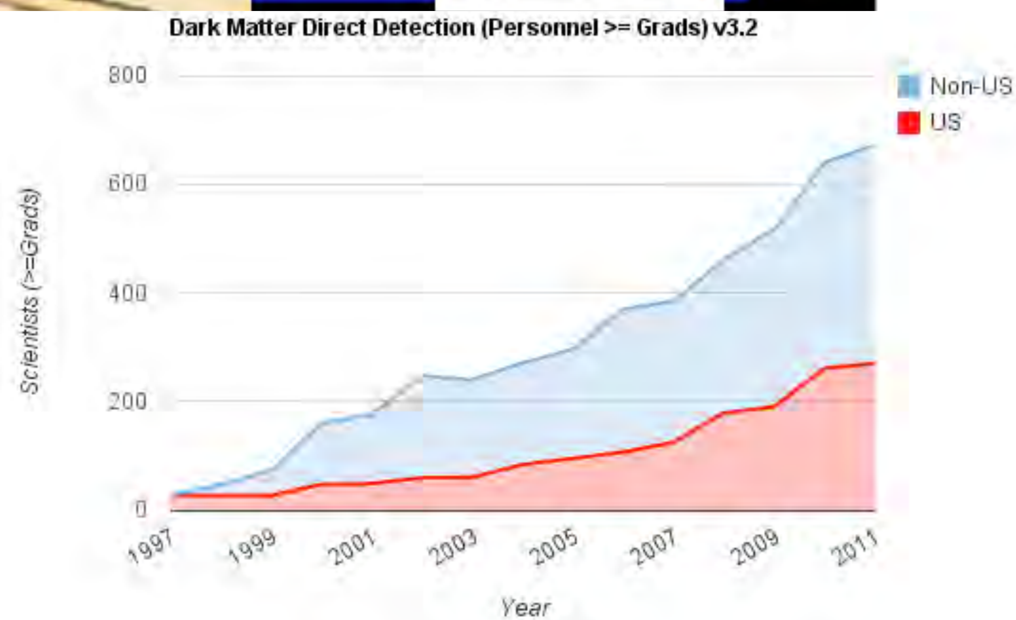
Fermi/GLAST

WIMP scattering on Earth:e.g. Super CDMS,LUX etc.

An Active Field

Credit: Joerg Jaeckel





Direct Detection
An expanding community

2011 US≈ 270 physicists
≈70% FTE
Now?

Where Are We ?

At High Mass

Nothing so far

Broadly consistent with the absence of SS observation at LHC

Focus point solution in CMSSM ≈10^{-45} is mostly excluded

Low Mass

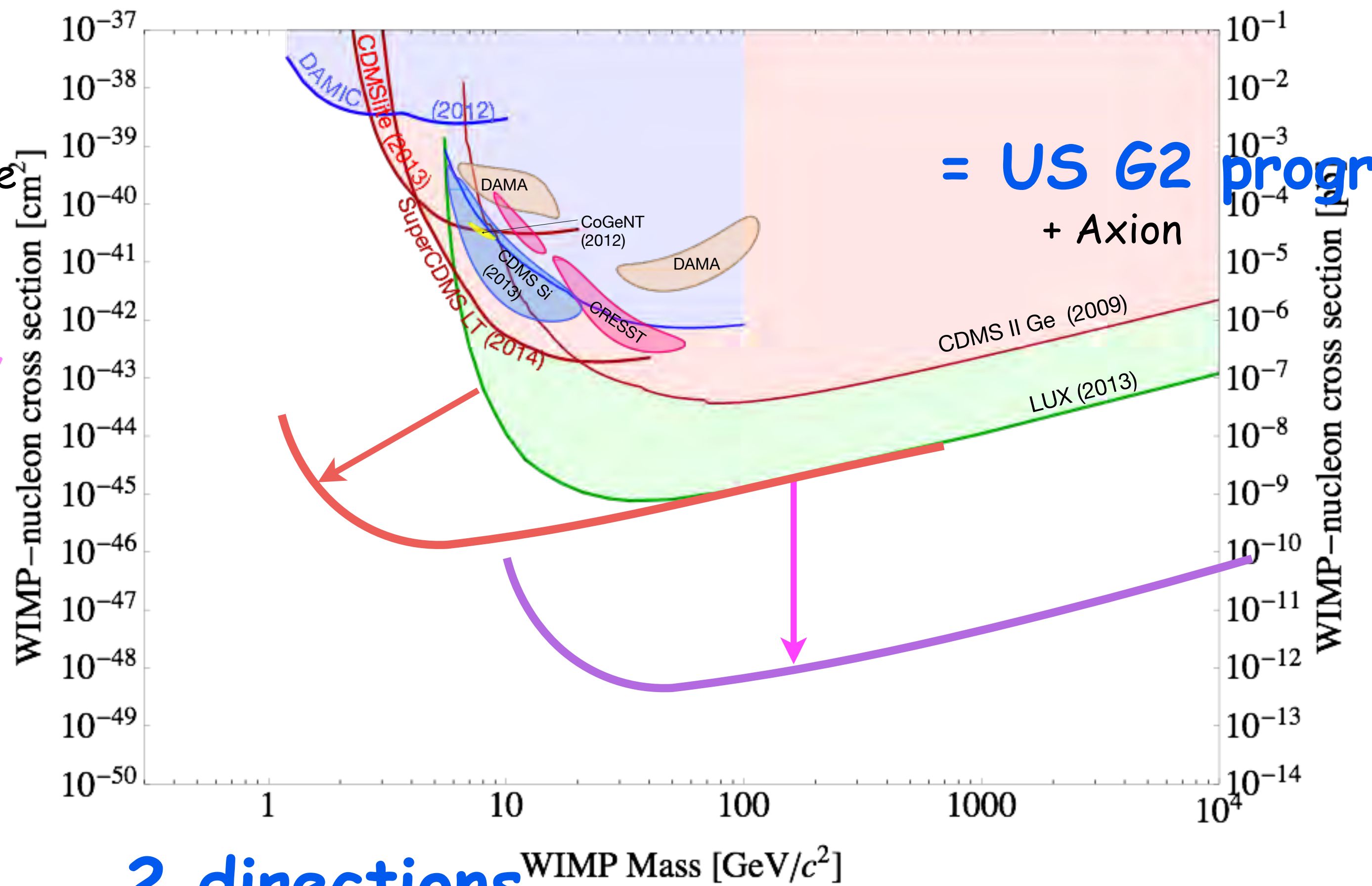
A number of closed contours, and strong limits

What is going on?

Close to threshold: Outliers ?

Excluded by
- XENON 100
- LUX
- SuperCDMS Soudan
- CDEX

CDMS does not see any significant modulation



2 directions

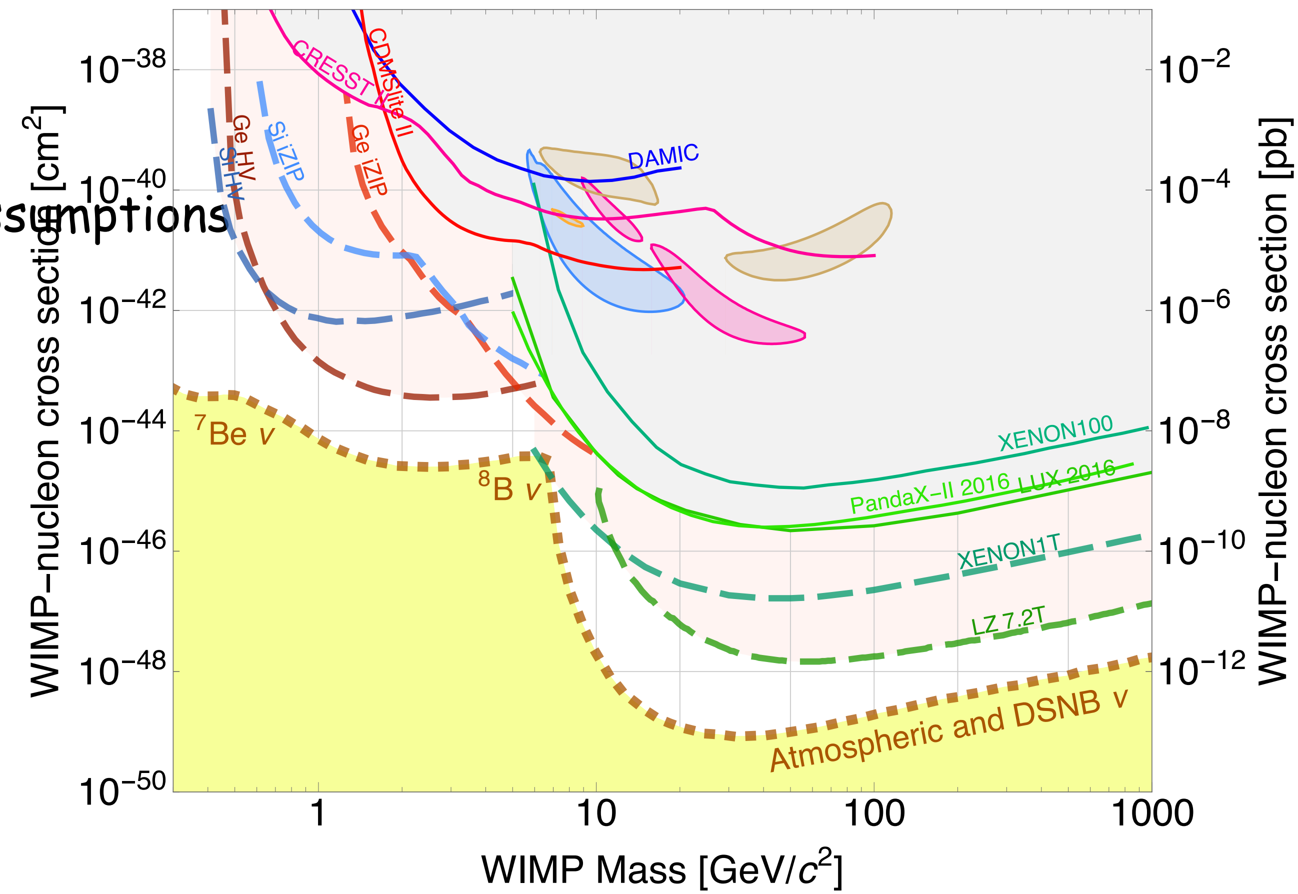
1. Improve sensitivity at large mass

2. Improve sensitivity at small mass

G2 WIMP Sensitivity

US G2 + Equivalent

Xenon 1T + 7T
XMASS 1.5T 2017, 7T 2019
Not all same statistical assumptions



SuperCDMS+Eureca

Serious discussion of merging at SNOLAB.
The cryostat is designed to allow such upgrades

Neutrino floor

None of these experiments reach the "neutrino floor" which assumes subtraction by a factor ≈20

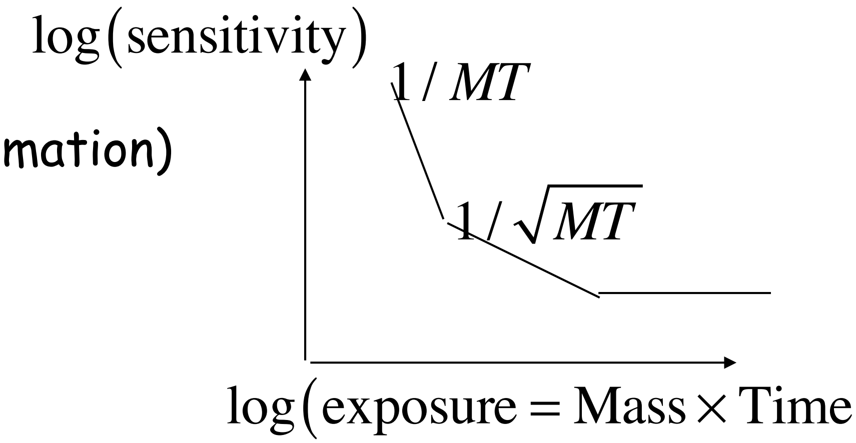
^{8}B coherent neutrino scattering would be interesting: Proof of sensitivity + observation of Coherent Neutrino Scattering

SuperCDMS= Low Mass
LZ = High Mass
approaching "neutrino floor"

Basic Challenges

Lessons learned in the last few years

Need to have critical mass (target, scientists)
Need for good calibration (yields)
Need for good understanding of backgrounds
Difficulty from outliers (need redundant information)



How to get unambiguous results?

The goal should be negligible background!
We should not abandon blind analyses:
only unbiased way
Use likelihood methods to get confirmation of a signal
But extremely sensitive to background model. What about the unknown unknowns?
Use knowledge acquired about leaking backgrounds to design better detectors

Complementarity of experiments ≠ budgetary constraints

Real proof requires 2 experiments, which are as different as possible but overlap in sensitivity
We should pursue both the low and high mass regions (different paradigms)
We need a variety of targets to elucidate couplings and protect against cancellation. Xe, Ge,Ar
Missing F, or Na in US G2 but PICO

Further Out Ideas: Reaching Neutrino Floor

At high WIMP mass

greater target mass with appropriate reduction of the background (radon emanation, ^{39}Ar)

- 20T -50T of Argon
- Darwin: Xe+ Ar
- PICO (cheap)
- H_2O_2 detectors (Druikier) for neutrino geology: extremely cheap?

At low mass

plenty of mass,

but need to

- maximize energy sensitivity e.g., with Luke-Neganov amplification in SuperCDMS HV approach
- reduce background
- restore background rejection (Matt Pyle)
    - SuperCDMS HV: increase phonon resolution down to 10eV
    - Phonon only iZIP with phonons measuring separately ionization and initial phonons
- challenge of "dark current" (e.g., IR, injection, metastable auto-ionization state): reject ionization (or phonon) only pulses

- Liquid He (McKinsey,Seidel)
- Phonon+scintillation (Derenzo)

Simpler low mass ideas? **e.g. large gas spheres (Gerbier,Giomataris arXiv:1512.04346)**

Even Further Out Ideas

Directionality for conventional WIMPs (J. Billard)

If WIMP is at high mass: 10 tons of low pressure gas (100 torr)=10,000m^3 with cubic mm pixels. Clever schemes based e.g., on CCDs

Even, DNA (Druikier) which through sequencing tricks could provide nm resolution

Go drastically lower in mass ≈ keV (warm dark matter)

Kathryn Zurek/Matt Pyle: breaking Cooper Pair in superconductors

difficulty of dealing with single quanta (cf. QBits)

Axion-like particles

Peter Graham and Surjeet Rajendran

time varying nuclear electric dipoles which would precess in an electric field (cf NMR)

+ Dima Budker et al.: Phys. Rev. X 4, 021030 (2014) arXiv:1306.6089

CASPEr =>very low mass axions 10^{-9} to 10^{-6} eV

Dark Photons as Dark Matter

Peter Graham and Surjeet Rajendran: Hidden Electric Field

Radio in a Faraday cage

+ Kent Irwin Phys. Rev. D 92, 075012 (2015) arXiv:1411.7382v2

Sub eV Dark Matter Workshop

Conclusions

Importance of the 13 TeV LHC run

- Discovery of supersymmetry: still possible
- No supersymmetry (750 GeV di-gamma?)

    Even larger importance of direct detection -> Dark Sector (low mass) + High Mass

Impressive technical progress (Gaitskell plot)

<= R&D!

Importance of G2 + equivalent program

- Pushing both down and left

Do not be afraid to be creative

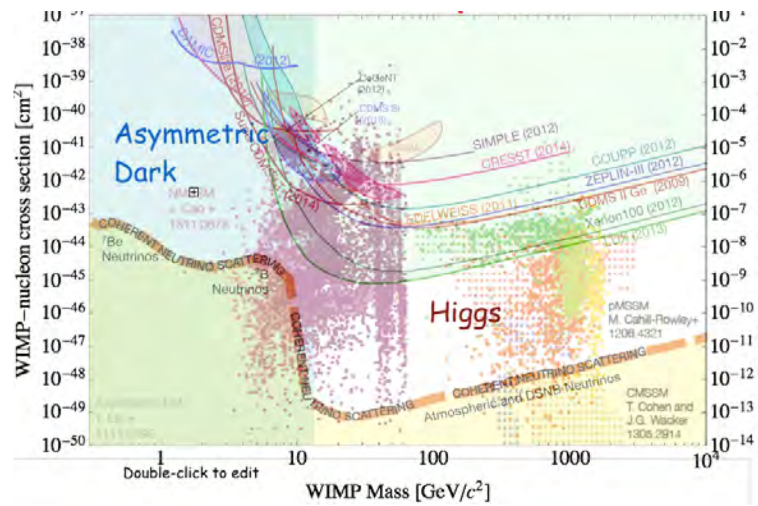
- Search broadly, not only under the theoretical lamp post
- R&D is essential!
- However, try to reach critical mass: unambiguous results

Additional Material

Recent Input from Particle Physics

cf. Michele Papucci's talk

Higgs at 126 GeV/c



No sign for supersymmetry

CMSSM too simple ->pMSSM,NSSM

Crisis of naturalness?

No evidence from mono-jets,mono-γ's

Note: Limits assumes high mass mediator

Dark Sector models have typically low mass mediators

Complementarity with "Dark Photon" searches

Basic complementarity

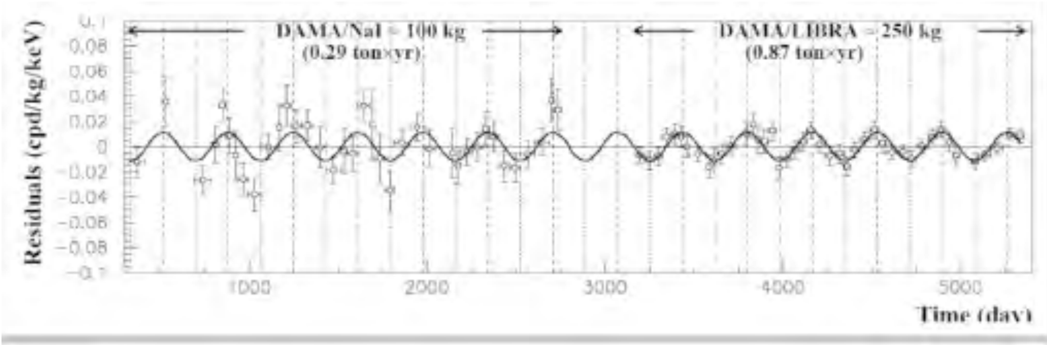
LHC probes well:

- monojets if high mass mediated
- masses below $m_H/2$
- intermediate mass in decay of gluinos (≈6x LSP), but needs to produce it!

Direct Detection:

- light mediators are OK
- loses only linearly at high mass

NaI: How to prove/disprove DAMA



Clearly modulation

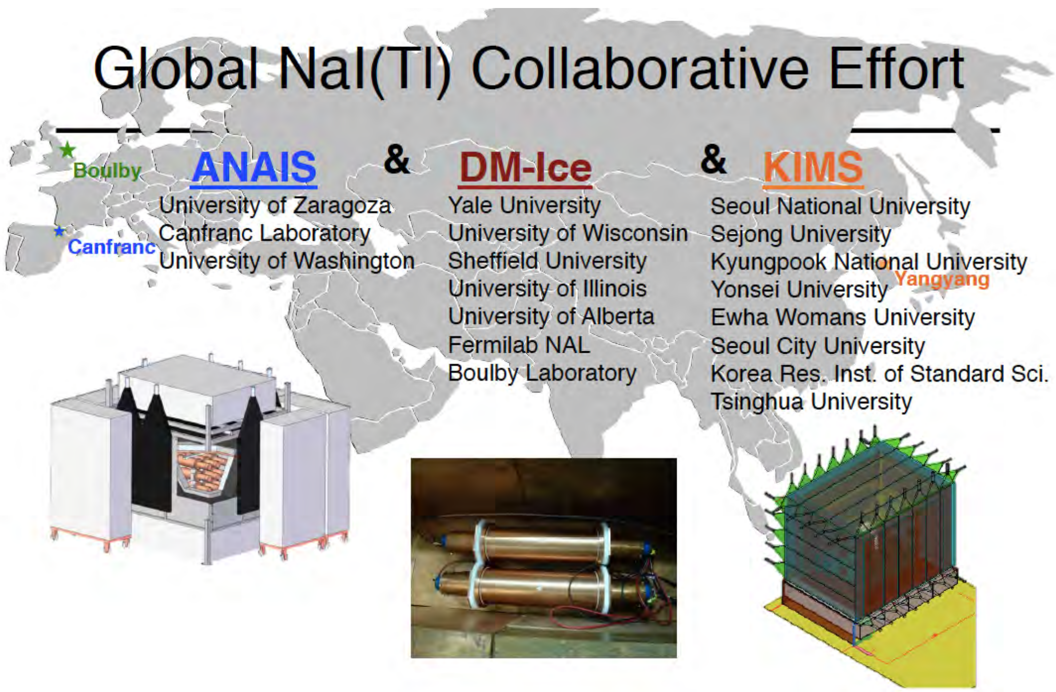
although not blind

Is it Dark Matter or instrumental?

How do we make progress?

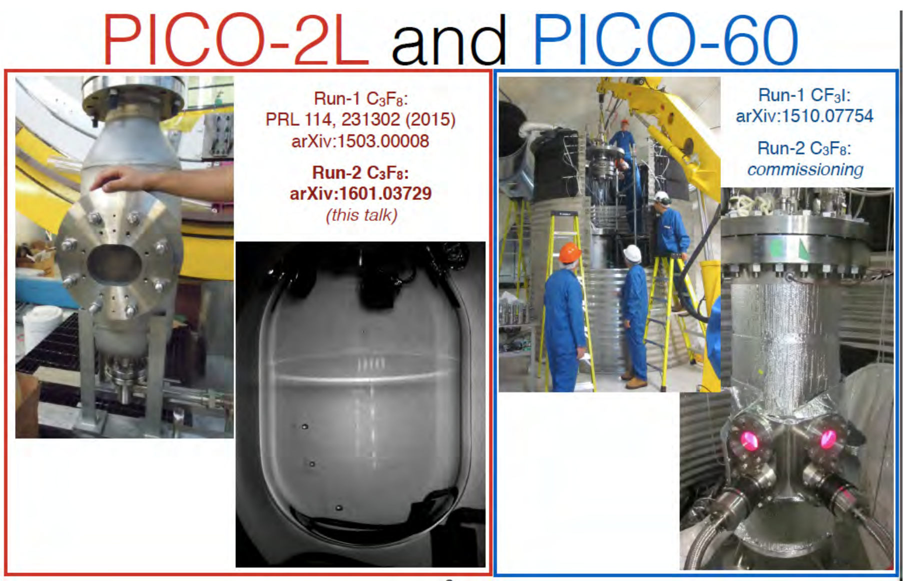
Lower threshold: LIBRA has changed Phototubes to high QE Results 2017

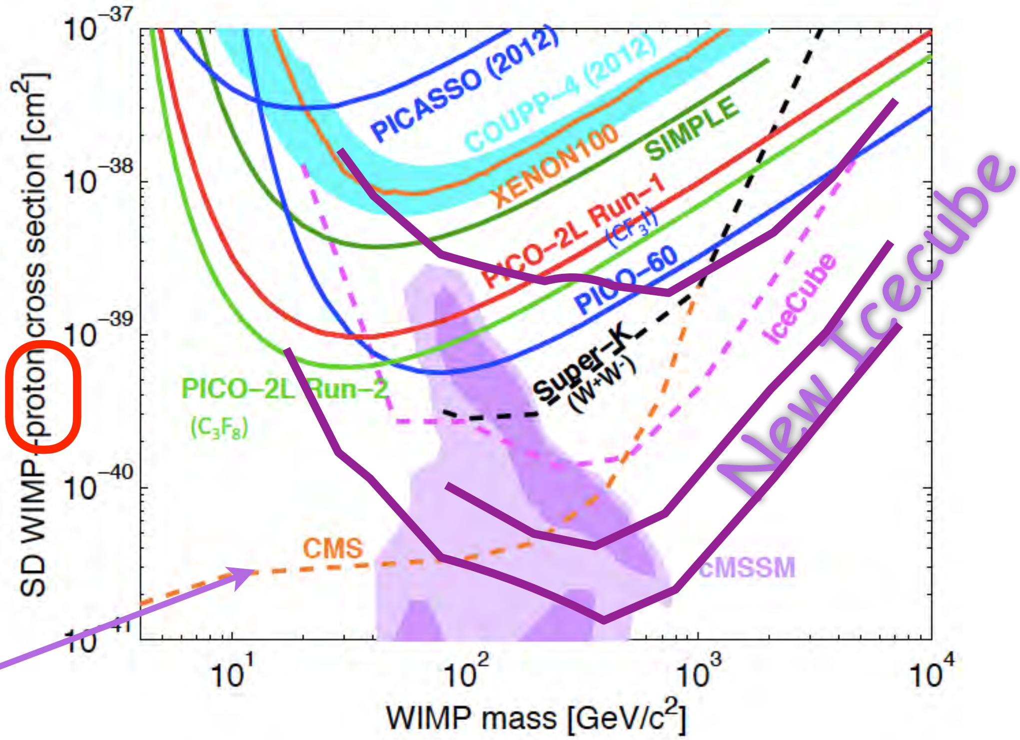
Experiment by other groups: DM-Ice,ANAIS,KIMS, Princeton



Spin Dependent

Finally entering SUSY region





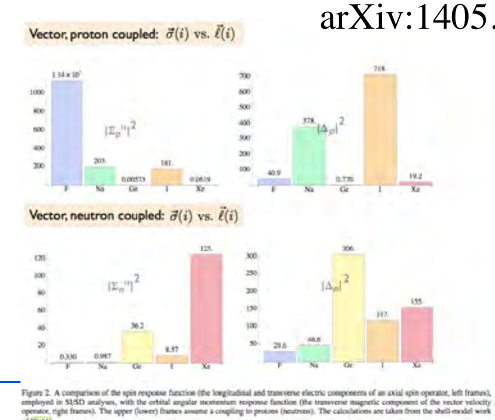
LHC Monojets

$$e.g.(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

Heavy mediator

Finally entering SUSY region

arXiv:1405.6690

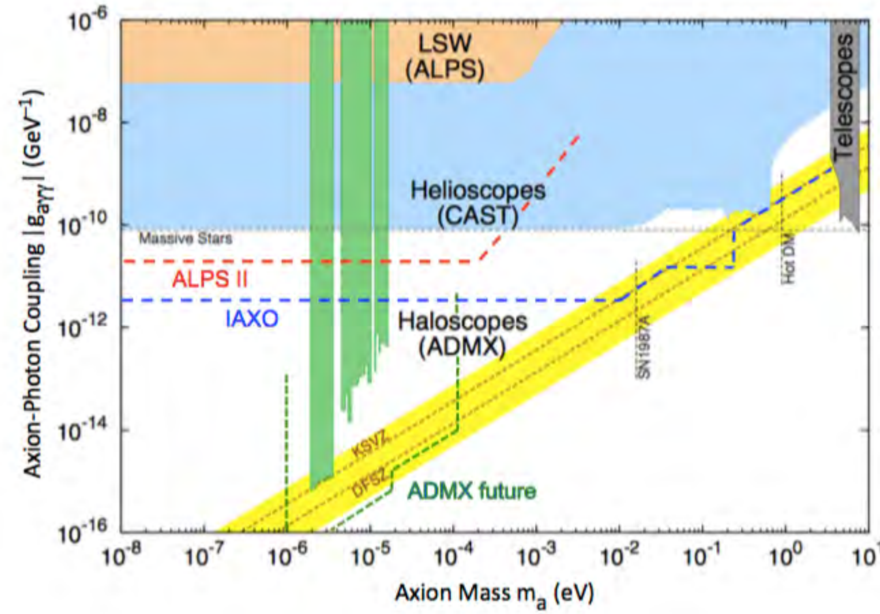


Note that SD proton/neutron is an approximation

Many more couplings than axial vector coupling
Velocity dependent effects (including Fermi)
cf Haxton, Zurek

Axions

Recent article Graham et al. arXiv:1602.00039



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